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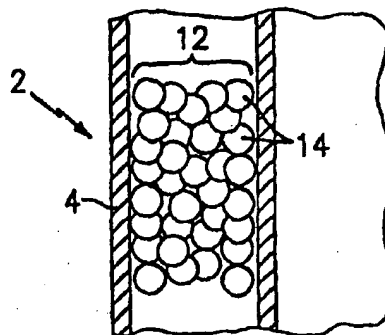
## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

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(21) International Application Number: <b>PCT/US99/26558</b> (22) International Filing Date: <b>10 November 1999 (10.11.99)</b> (30) Priority Data: <b>09/190,855</b> <b>10 November 1998 (10.11.98)</b> <b>US</b> (71) Applicant: <b>INTERNATIONAL FUEL CELLS, LLC [US/US];</b> <b>195 Governor's Highway, South Windsor, CT 06074 (US).</b> (72) Inventors: <b>LEISIEUR, Roger, R.; 14 Van Buren Road, Enfield,</b> <b>CT 06082 (US). SETZER, Herbert, J.; 17 Virginia Drive,</b> <b>Ellington, CT 06029 (US).</b> (74) Agent: <b>KELLY, Robert, H.; Intellectual Property Counsel,</b> <b>Hamilton Sundstrand, One Hamilton Road, Mail Stop</b> <b>1-1-BC18, Windsor Locks, CT 06096 (US).</b>	(81) Designated States: <b>AL, AM, AT, AU, AZ, BA, BB, BG, BR,</b> <b>BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GD,</b> <b>GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP,</b> <b>KR, KZ, LC, LK, LR, LS, LT, LU, LV, MD, MG, MK,</b> <b>MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG,</b> <b>SI, SK, SL, TJ, TM, TR, TT, UA, UG, UZ, VN, YU, ZW,</b> <b>European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR,</b> <b>GB, GR, IE, IT, LU, MC, NL, PT, SE).</b>  <b>Published</b> <i>With international search report.</i> <i>Before the expiration of the time limit for amending the</i> <i>claims and to be republished in the event of the receipt of</i> <i>amendments.</i>	

(54) Title: **INHIBITION OF CARBON DEPOSITION ON FUEL GAS STEAM REFORMER WALLS**

## (57) Abstract

A fuel gas reformer assembly for use in a fuel cell power plant includes fuel gas passages (2), which contain a particulate alumina packing (12) in which a vaporized steam-hydrocarbon fuel stream mixture is heated. The walls (4) of the passages (2) have an alumina coating which protects the walls (4) from corrosion. The coating (4) and packing (12) are overlain by an alkaline earth metal oxide layer that limits carbon build-up on the surfaces of the walls (4) and prevents premature clogging of the passages (2). The carbon build-up-limiting layer is formed on components of the reformer passages by applying a water-based slurry of alkaline earth metal compounds to the reformer passage surfaces, and then drying the slurry to solidify it. The coated packing material (14) is operative to convert any free carbon remaining in the gas stream to carbon dioxide, or carbon monoxide, thereby further limiting carbon deposition in the assembly.



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## Inhibition of Carbon Deposition on Fuel Gas Steam Reformer Walls

### Technical Field

This invention relates to a fuel gas steam reformer assemblage and a method for forming the same. More particularly, this invention relates to a fuel gas steam reformer assemblage wherein the reformer gas passages are washcoated with a composite  
5 carbon-resistant alumina and alkaline earth metal oxide coating.

### Background Art

Fuel cell power plants include fuel gas steam reformers which are operable to catalytically convert a fuel gas, such as natural gas or heavier hydrocarbons, into the  
10 primary constituents of hydrogen and carbon dioxide. The conversion involves passing a mixture of the fuel gas and steam through a catalytic bed which is heated to a reforming temperature which varies depending upon the fuel being reformed. Catalysts typically used are nickel catalysts which are deposited on alumina pellets. There are three types of reformers most commonly used for providing a hydrogen-rich gas stream  
15 to fuel cell power plants. In addition, hydrocarbon fuels may be converted a hydrogen-rich gas stream by use of a partial oxidation reaction apparatus. These are a tubular thermal steam reformer, an autothermal reformer, and a catalyzed wall reformer. A typical tubular thermal steam reformer will consist of a plurality of reaction tubes which are contained in a housing that is insulated for heat retention. The reaction tubes are  
20 heated by burning excess fuel gas in the housing and passing the burner gas over the reaction tubes. The reforming temperature is in the range of about 1,250°F to about 1,600°F. The individual reaction tubes will typically include a central exhaust passage surrounded by an annular entry passage. The entry passage is filled with the catalyzed alumina pellets, and a fuel gas-steam manifold is operable to deliver the fuel gas-steam  
25 mixture to the bottom of each of the entry passages whereupon the fuel gas-steam mixture flows through the catalyst beds. The resultant heated mixture of mostly hydrogen and carbon dioxide gas then flows through the central exhaust passages in

each tube so as to assist in heating the inner portions of each of the annular catalyst beds; and thence from the reformer for further processing and utilization.

5 A typical autothermal reformer may be a single bed or a multiple bed tubular assembly. Autothermal reformers are often used when higher operation temperatures are required for the reforming process because the fuel to be processed is more difficult to reform. In an autothermal reformer, the reaction gasses are heated by burning excess fuel within the reaction bed by adding air to the fuel and steam mixture so that the remaining fuel-steam mixture is increased to the temperature necessary for the fuel processing  
10 reaction. Typically, wall temperatures in an autothermal reformer are in the range of about 1,400°F to about 1,800°F. Such tubular reformers are disclosed in U.S. Patent No. 4,098,587.

A third type of prior art reformers have utilized catalyzed wall passages such as disclosed in U. S. Patent No. 5,733,347. Such reformers are formed from a sandwich of  
15 essentially flat plates with intervening corrugated plates which form reformer gas passages and adjacent regenerator-heat exchanger passages. Each of the reformer passage plate units is disposed directly adjacent to a burner passage plate unit so that the adjacent reformer and burner passages share a common wall.

Besides the reformer devices described above, a partial oxidation reaction apparatus  
20 may also be used to produce a hydrogen-rich fuel stream. This device is typically a chamber that is fed a hydrocarbon fuel, steam and oxidant source, usually air, so that the mixture spontaneously partially oxidizes to form a hydrogen-rich mixture. Such devices, for example, are disclosed in PCT application WO 98/08771.

Each of the aforesaid prior art reformer structures may suffer from carbon buildup and  
25 deposition on the surfaces of internal components of the reformer assemblies. Carbon buildup will clog the gas passages of the reformer ultimately, and will limit the effective service life of the reformer and thus the fuel cell power plant assembly which includes the reformer. It would obviously be desirable to produce reformer assembly

components, and a method for forming such components, which would result in a reformer assembly which would be resistant to carbon build-up on surfaces of the reformer.

#### Disclosure of the Invention

- 5 This invention relates to a composite coating, and a method for forming the same, for use in fuel cell steam reformer assemblies which will result in decreased or no carbon deposition on reformer components that are covered by the composite coating. The composite coating includes an underlying alumina component and an outermost carbon formation-inhibiting metal oxide component. The reformer assembly will have its interior
- 10 steel walls coated with the alumina component, and the alumina component will have an amorphous or polycrystalline metal oxide layer formed over the underlying alumina component. Certain passages in the reformer assembly can also be provided with a metal oxide particulate bed that promotes the conversion of carbon in the steam-fuel mixture to carbon monoxide, which is subsequently converted to carbon dioxide.
- 15 The metal oxide which is used for the carbon deposition-inhibiting coating is preferably an alkaline earth metal oxide such as CaO or MgO; mixtures of alkaline earth metal oxides such as  $(\text{CaO})_X (\text{MgO})_Y$ , where "X" and "Y" are numbers between 0 and about 1; an alkaline earth metal oxide substituted with an alkali metal oxide such as  $\text{Na}_X \text{Ca}_{(1-X)} \text{O}$ , wherein "X" is a number between 0 and about 0.2; a rare earth oxide such as
- 20  $\text{La}_2\text{O}_3$  or  $\text{CeO}_2$ ; a rare earth oxide substituted with other rare earths, such as  $\text{Gd}_X \text{Ce}_{(1-X)} \text{O}_2$ , wherein "X" is a number between 0 and about 0.2; a rare earth substituted with alkaline earths such as  $(\text{CaO})_X \cdot \text{La}_2\text{O}_3$ ; and/or metals from the Periodic Table Group VIII transition metals, such as  $(\text{NiO})_X \cdot \text{La}_2\text{O}_3$ , wherein "X" is a number between 0 and about 1.0.

Typical compositions are as follows:

TABLE 1

	Compound	Examples	Tested Values	Range of Values
	<u>alkaline earth metal oxides</u>	$(\text{CaO})_X \cdot (\text{MgO})_Y$	pure	X and Y are between 0.0 and
5	<u>about 1.0</u>			
	<u>substituted alkaline earth</u>	$\text{Na}_X \text{Ca}_{(1-X)} \text{O}$	0.08	X is between 0.0 and
	<u>about 0.2</u>			
	<u>metal oxides</u>			
	<u>rare earth oxides</u>	$\text{CeO}_2$ or $\text{La}_2\text{O}_3$	pure	
10	<u>rare earth oxides substituted</u>	$\text{Gd}_X \text{Ce}_{(1-X)} \text{O}_2$		X is between 0.0 and
	<u>about 0.2</u>			
	<u>with rare earths</u>			
	<u>rare earth oxides substituted</u>	$(\text{CaO})_X \cdot \text{La}_2\text{O}_3$	0.2	X is between 0.0 and about
	<u>1.0</u>			
15	<u>with alkaline earths</u>			
	<u>rare earth oxides substituted</u>	$(\text{NiO})_X \cdot \text{La}_2\text{O}_3$	0.15	X is between 0.0 and about
	<u>1.0</u>			
	<u>with group VIII transition metals</u>			

The metal oxide coating will be formed as an amorphous or polycrystalline coating which is derived from a solution of a nitrate, acetate or citrate salt of the metal which is dissolved in water, and in which a hydroxide of the metal is suspended to form the slurry. The hydroxide may be added as a metal hydroxide or formed by addition of less than a stoichiometric amount of a base such as NaOH or  $\text{NH}_4\text{OH}$  to the solution which may result in a slurry or a sol-gel mixture with a percentage of soluble salts in the solution. A small amount of a surfactant is added to the slurry to aid in the dispersion of the hydroxide and increase the wetting of the reformer surfaces in question by the slurry.

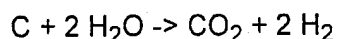
In order to form a calcium oxide coating,  $\text{Ca}(\text{OH})_2$  solid is mixed with a concentrated solution of  $\text{Ca}(\text{NO}_3)_2 \cdot 5 \text{H}_2\text{O}$  to form the slurry. To form a lanthanum-nickel oxide coating, a solution of nickel acetate and lanthanum nitrate is made with the desired

cation ration. The slurry is made by adding ammonium hydroxide which co-precipitates a portion of the nickel and lanthanum as a hydroxide. Often, the precipitate initially occurs as a sol-gel which, upon standing, ripens into a slurry. The reformer surfaces in question may be coated by the suspension in either the sol-gel state or the slurry state.

- 5 Subsequent heat treatment of the coating will convert the coating to a polycrystalline or amorphous form. When proper proportions of the nitrate and the hydroxide are used, the resultant amorphous coating, when dried, will not chip or flake off of the underlying alumina layer. By utilizing the aforesaid carbon-inhibiting coating, carbon deposition on the walls of the reformer passages from the fuel being processed is greatly reduced, or  
10 eliminated.

Certain of the passages may also be provided with a metal oxide particulate constituent which is operable to convert carbon in the fuel-steam stream to carbon oxides. The metal oxide particulate material can take the form of pellets, typically spheres, rings or cylinders which are coated with calcium oxide, or any of the aforementioned

- 15 compounds. The carbon conversion reaction in question is as follows:



- It is therefore an object of this invention to provide an improved carbon deposition-inhibiting coating for a reformer assembly, and a reformer assembly which includes the  
20 improved coating.

It is another object of this invention to provide a method for forming a flaking and spall-resistant carbon deposition-resistant coating on walls of a fuel gas-steam stream conduit in a fuel cell fuel gas reformer assembly.

#### Brief Description of the Drawings

- 25 These and other objects and advantages of this invention will become readily apparent to one skilled in the art from the following detailed description of a preferred embodiment of the invention when taken in conjunction with the accompanying drawings in which:

FIG. 1 is a fragmented cross-sectional drawing of a fuel gas reformer passage which is formed in accordance with this invention; and

FIG. 2 is a fragmented enlarged sectional view of the side wall of the passage of FIG. 1 showing the coatings deposited on the interior of the passage wall.

#### Specific Mode For Carrying Out The Invention

Referring now to the drawings, there is shown in FIG. 1 a fragmented cross-sectional view of a portion of a fuel processing assembly passage denoted generally by the numeral 2, which forms a part of a fuel-steam mixture reformer assembly component in a typical fuel cell power plant that has been adapted in accordance with this invention.

10 The walls 4 of the reformer passages 2 are preferably formed from an aluminized steel material, or a steel based alloy containing aluminum. As seen in FIG. 2, the interior surfaces 6 of the reformer passage walls 4 are provided with a coating 8 of alumina which serves to protect the steel from corrosion. The aluminized coating 8 is formed by a conventional aluminizing process, as described in ASTM B875, and the addition of the  
15 heat treating step which is performed at about 1,825°F for a time period in the range of about two to about twelve hours. The aluminization and subsequent heat treatment steps combine to form a continuous adherent porous aluminum oxide coating on the steel. Such a surface is an ideal surface upon which to deposit a carbon deposition-inhibiting alkaline earth metal oxide material layer.

20 Selected portions of the porous alumina coating 8 are overlain and penetrated by an amorphous layer 10 of calcium oxide; magnesium oxide; a lanthanum-nickel oxide composite; alkali metal-substituted alkaline earth metal oxides such as sodium-substituted calcium oxide; and the like. The layer 10 is operable to retard or prevent carbon from depositing directly from the fuel-steam stream onto the heated walls of the  
25 passages 2 during reformer operation.

Passages 2 of a length required to raise the gas to the reformer inlet temperature will be filled with a particulate packing bed 12 which is formed from metal oxide pellets 14 of:



calcium oxide coated onto an alumina substrate; a calcium oxide/iron oxide composite coated onto an alumina substrate; or other compounds, as noted above.

The following is a description of a method for forming the desired carbon-inhibiting layer in the flow passages 2. Calcium nitrate is very soluble in water, while calcium hydroxide is not. Calcium nitrate, alone, forms a waxy hygroscopic solid. Calcium hydroxide alone forms a white crystalline powder. This invention operates in a best mode with a certain concentration of calcium hydroxide-to-calcium nitrate, at which concentration, a slurry of the calcium hydroxide, in a solution of the calcium nitrate in water, gels and solidifies when heated.

- 10 Calcium hydroxide powder was added to a calcium nitrate solution to form a slurry. The slurry was painted onto the tube surfaces to be coated. As the temperature was raised, the calcium hydroxide solubility increased while the solution lost water, and thus was concentrated. Together, calcium nitrate and calcium hydroxide form a solid, amorphous or polycrystalline coating which is desirable.
- 15 Exemplary details of the aforesaid procedure are as follows. About five hundred grams of  $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$  (calcium nitrate tetrahydrate) were mixed with about three hundred thirty grams of distilled water in a one liter wide mouth plastic bottle. About 0.3 grams of concentrated  $\text{HNO}_3$  was added to the aforesaid mixture. The solution was cooled and mixed until the tetrahydrate was dissolved in the water and acid. About sixty six grams  
20 of  $\text{Ca}(\text{OH})_2$  were added to the water-acid-tetrahydrate solution, and the resultant mixture was shaken whereupon the mixture gelled, and then became fluid after standing for about one to two hours at room temperature. About 1.3 to about 1.4 grams of the surfactant "TRITON X-100" was added to the fluid mixture and the mixture was shaken well before using. The reformer tubes to be coated were washed with a Liquinox®  
25 detergent and then wetted with water. The washed tubes were scoured with a beaker brush. The washed and scoured tubes were rinsed in water (about 30° to about 40°C). The uniformly wetted tubes were dried at a temperature of 240°F, and cooled to room temperature. The surface to be coated was then painted with the slurry, using a wetted

paint brush so as to minimize the amount of foam from the slurry. A thin coat was applied and excess liquid was removed with a dry paint brush. The coated parts were then heated to a temperature of 110°C in an air oven, making sure to allow the coating to reach the aforesaid temperature. The dried coated parts were then stored in an atmosphere having a relative humidity of less than 60%.

If the ratio of nitrate-to-hydroxide in the slurry is too high, a waxy coating is obtained. A ratio of 20-to-1 nitrate-to-hydroxide produces waxy coatings. If the aforesaid ratio is too low, then powdery coatings are obtained. A ratio of 16-to-1 nitrate-to-hydroxide produces powdery coatings. A ratio of 18-to-1 nitrate-to-hydroxide results in a clear amorphous coating which is solid to the touch, and which, when heated to the decomposition temperature, i.e., greater than about 1,380°F, does not spall.

Since many changes and variations of the disclosed embodiment of the invention may be made without departing from the inventive concept, it is not intended to limit the invention other than as required by the appended claims.

## Claims

1. A hydrocarbon fuel gas steam reformer assembly comprising one or more fuel gas passages for receiving a mixture of fuel gas and steam, said fuel gas passages being provided with an alumina coating which protects an interior of said fuel gas passages against corrosion, and at least portions of said alumina coating being overlain by a coating of an alkaline earth metal oxide which coating inhibits carbon deposition in said fuel gas passages.
2. The reformer assembly of Claim 1 wherein said gas passages include an outer steel or steel alloy component.
3. The reformer assembly of Claim 1 wherein said alumina coating is porous.
4. The reformer assembly of Claim 3 wherein said metal oxide coating penetrates pores in said alumina coating.
5. The reformer assembly of Claim 1 wherein said alkaline earth metal oxide is  $\text{CaO}$ ,  $\text{MgO}$ ,  $(\text{CaO})_x(\text{MgO})_y$  and wherein X and Y are in the range of 0 to about 1.0.
6. A method for forming a carbon deposition-resistant component which is designed for use in a hydrocarbon fuel reformer, said method comprising the steps of:
  - a) providing a component which has an alumina surface;
  - b) providing a solution of one of an alkaline earth metal compound and an alkaline earth metal oxide;
  - c) coating said component with said solution; and
  - d) heating said coated component so as to convert said solution into an amorphous or polycrystalline coating on said alumina surface.
7. The method of Claim 6 wherein said alumina surface is porous and said solution penetrates said porous alumina surface so as to bind firmly to the latter.

8. The method of Claim 7 wherein said solution is a solution of soluble salts containing alkaline earth metal ions.

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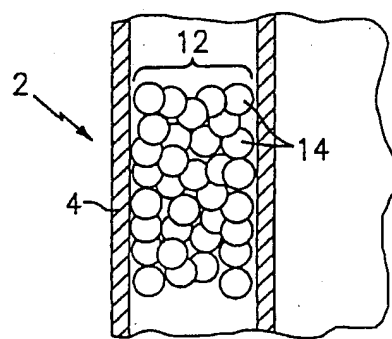


FIG. 1

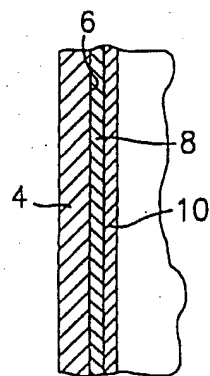


FIG. 2

## INTERNATIONAL SEARCH REPORT

International application No.  
PCT/US99/26558

<b>A. CLASSIFICATION OF SUBJECT MATTER</b> IPC(7) : B01D 50/00; C01D 1/00 US CL : 422/168, 240, 241; 23/302R According to International Patent Classification (IPC) or to both national classification and IPC														
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<b>C. DOCUMENTS CONSIDERED TO BE RELEVANT</b>														
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No												
X	US 3,791,143 A (KEITH et al) 12 February 1974, col. 1, lines 1-25 and col. 8, lines 13-17.	1, 3-4												
Y		2, 5-8												
Y	US 5,486,428 A (GARDNER et al) 23 January 1996, col. 15, lines 3-16.	2												
Y	US 4,292,049 A (TANAKA et al) 29 September 1981, col. 1, lines 12-48.	5-8												
Y	US 3,760,933 A (MALDEIS et al) 25 September 1973, col. 6, lines 3-27.	5-8												
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